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Highlights: We introduce an innovative methodology for reconstructing tree stems from terrestrial LiDAR data. The method uses a multi-scale combination of an original Hough transform and active contours. Tests were conducted on both simulated data and real LiDAR data. Even though no formal evaluation was completed yet, the procedure seems promising.

Key words: *terrestrial LiDAR, stem reconstruction, Hough transform, open active contours*

Introduction

Tree structural attributes are crucial to forest inventories measurements. Indeed, structural attributes such as diameter at breast height (DBH) or stem taper are used in a wide range of applications. For example, they are employed in forest monitoring, plant growth models and allometric models [1]. However, the measurement of some of these attributes is often limited in the context of non-destructive field work, and their precision can also be limited by measurement tools and operational constraints. Thus, terrestrial laser scanners (TLS) have been introduced as a measuring tool to expand the number and the quality of the structural attributes available in forest inventories. TLS instruments provide a precise 3D point cloud characterizing the surrounding environment of a forest plot from which tree attributes can be estimated in an non-destructive and objective way.

Assuming that tree stem cross-sections are circular, DBH and stem taper can be estimated using pattern recognition algorithms applied to point clouds. Point cloud processing methods such as circle fitting, cylinder fitting or cone fitting are indeed well-suited for reconstructing tree stem [2]. Hough transform is another way of retrieving DBH from point clouds [3]. Traditional Hough transform has shown a stem detection rate above 90% and an average DBH estimation error of 1.7 cm when applied to natural forest environment [3]. The analysis of the Hough space obtained by Hough transform can be a hard task, hence, despite these positive results, shape fitting has become the main method to reconstruct tree stems. However, Hough transform, as a pattern recognition tool, has demonstrated to be adapted for application in complex forest environment.

In this study we aim at developing a novel methodology for tree stem reconstruction in order to estimate DBH and stem taper. This methodology is intended to be able to overcome some limitations of point cloud analysis: occlusion, non-homogeneous sampling density and noise. To do so, we take advantage of the Hough transform qualities and propose an innovative use of this pattern recognition tool.

Material and methods

We reconstruct tree stems as an ordered series of circles in the 3D space with continuous centre locations, orientations and radii, which we refer to as tuboid. We introduce a multi-resolution approach for extracting such series of circles from the TLS point cloud data. At each resolution, in a first step, a Hough space describing potential circles in the data is created. In a second step we employ growing open active contours to extract tuboids from this space.

We use a variant of the classical Hough transform adapted to circle detection based on normal direction at each point of the data to obtain a discrete 4D Hough space (HS). A cell (x,y,z,r) of this space describes the number of data points belonging to the circle $c(x,y,z,r)$. The Hough space is computed according to the following property: the normal direction at a point on a circle passes through the centre of this circle. This property allows creating the corresponding Hough space using fast ray tracing algorithms.

A tuboid in this HS is represented as a curve. Since the elements of the HS represent the number of points belonging to a circle, the elements of highest value tends to be an accurate reconstruction of the data. Thus, we intend to extract curves passing through high value elements. To do so, we use open active contours. We define a curve energy which is minimum when the curve passes through these high value elements with a low curvature in order to reduce noise effect and obtain a smooth taper. Classical active contours need an initialisation of their position. Such a general initialisation along a stem can be a delicate issue. Instead, we initialise small curves at the local maximum of the HS and let the active contours grow along the elements of high value by adding a growing term to the curves.

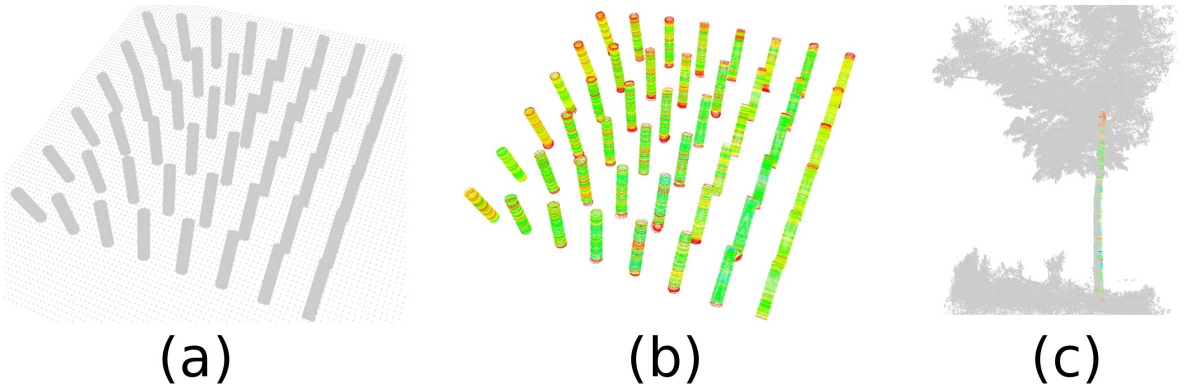

Figure 1 : (a) simulated point cloud : cylinders with increasing orientation angle and noise, (b) reconstruction with Hough transform (circles are coloured according to their value in the HS), (c) laser scanned tree stem and reconstruction as tuboid

The precision of results is related to the Hough space resolution. However, the computation of high resolution Hough spaces for 20 m × 20 m forest plots is time consuming and needs a lot of computer resources. This is why we propose a multi-resolution scheme. Starting from a coarse Hough space, coarse tuboids are extracted. Then, a precise sub-Hough space is computed with finer resolution.

Results

Up to now, the methodology was tested on both simulated and real datasets. The first test dataset is a simulated point cloud containing a set of 48 cylinders with a constant radius (50 cm) with various orientations and increasing noise (from 0% to 10% of the radius). The second dataset is a single-scan acquired point cloud in a real forest environment using the Faro Focus 3D TLS (Fig. 1).Normal directions have been estimated by local plane fitting for both dataset. The 48 cylinders of the first data set were successfully reconstructed with an average error of 1.07 cm. This illustrates the robustness of the HT to noise (Fig. 1). In the second data set from real data, tree stem from the ground to the centre of the crown.

Discussion

The method we introduce is based on a combination of two powerful pattern recognition tools. Our variant of the classic HT needs an estimation of the normal at each points of the cloud. Thus, the results are highly dependent on the quality of the normal estimation procedure. However, this HT has a low algorithmic complexity due to to the availability of the normal information: the number of necessary operations is linearly related with *n,* the number of points in the cloud. Moreover, HS elements contain only local information, and HS analysis with active contours is based on the detection of local high values, making the entire methodology able to deal with non-homogeneous sampling density.

The use of growing open active contours ensures a continuity of location, orientation and radii inside each tuboid following what is observed for tree stem and branches. These growing active contours also avoid the issue of initialisation and the need of *a priori* information about the location of tree stems. Finally, through the minimization of the internal energy of curves and the addition of a growing term to the active contours, missing information in occluded areas may be coherently estimated according to the surrounding non-occluded zones.

Conclusion

We proposed a novel methodology to reconstruct tree stems from LiDAR data collected in forest plots. This methodology aims at overcoming problems related to the use of TLS in forest environment such as occlusion, non-homogeneous sampling densities and noise. By combining active contours with the Hough transform, we take advantage of their respective qualities in an innovative novel way. This treatment differs from the iterative shape fitting procedures since stem reconstruction is embedded in a single object recognition: a tuboid.

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